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Investigation into the applicability of a passive upper-limb exoskeleton in automotive industry

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Abstract

The fourth industrial revolution faces the technological challenge of human-robot cooperation in manufacturing process. Aim of this study was to investigate the effectiveness and user's acceptance of a passive exoskeleton for upper limbs. Three different tests, involving static and dynamic tasks, were performed by 29 automotive operators without and with the exoskeleton. Main aspects and results of the testing campaign are presented in the paper. Potential issues associated to the introduction of these auxiliary devices in the automotive industry are briefly addressed, together with the open questions on how to assess the biomechanical workload risk, especially in the design phase.

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Keywords: passive exoskeleton; upper limb; human-robot cooperation; ergonomic aid; usability; workload; manufacturing process.

1. Introduction

In industrial manufacturing processes, robotic solutions can perform tasks requiring large forces; however, they do not provide manipulation ability, dexterity, flexibility, problem-solving capacity and quality, which are proper of

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human beings. Thus, workers are still required to perform some manual assembling and handling activities. In this case, alternative measures are applied to assure that the manual tasks respect the ergonomic principles and to decrease workers' mechanical exposure to acute and cumulative occupational risk factors. To reduce the physical load, material handling aids can be used, such as balancers or cranes. Although effective to avoid musculoskeletal disorders, their use can be perceived as time and space consuming. Workers will tend not to use them if loads fall within their strength capacity, if the position of the device hinders movements and/or learning is required [1].

These considerations, in combination with an ongoing demographic change, suggest the need of new solutions to support the physical work of human operators. Technological evolution has progressed from automated systems to Human-Robot Collaboration, with the aim of safeguarding the wellbeing of the worker while optimizing productivity and system performance. Exoskeletons are an examples of Human-Robot Collaboration in which the device is worn by the human and the physical contact between the operator and the mechanical structure allows a direct exchange of mechanical power and information signals [2,3]. The exoskeleton technology originally focused on military [4,5] and rehabilitation [6–8] applications. Only in the last years, attention is paid to their application into manufacturing industry. The main benefit of exoskeleton is a good merge between human flexibility and robot power enhancing, without the need for robot teaching or programming [9], moreover they can be used when other traditional solutions are not usable or effective. Although many examples of exoskeletons are described and presented in the literature [5,10–12], their peculiar characteristics (weight, control, comfort, wearability, cosmetic, flexibility...) do not make them suitable to be used in industrial environments. Moreover there are no standards that manage industrial worker exoskeletons. Consequently, active exoskeleton-type solutions have potential for development as a work aid that augments workers' capacity, but due to the requirements of the industrial environment and the current lack of standards, their introduction in manufacturing industries is likely to occur only in some years.

Another matter are passive exoskeletons, which are potentially less effective but easier to introduce in the assembly line. They are lighter, no control is present and there is not the bottleneck of standards. Several passive devices are currently developed specifically to support shop floor workers. Many of them are prototypes and not yet engineered and available on the retail market. The PLAD (Personal Lift Assist Device) consists of elastic elements, the load is shared between the spine, shoulders, pelvis and lower extremities [13–15]. The Laevo [16] is a chest and back support exoskeleton that, thanks to flexible tubes, transfers part of the load from the lower back to the chest and to the legs. The Happyback [17] is made up of flexible fibreglass rods to which chest harness, belt and leg extensions are attached. The Bendezy [18] consists of an aluminum dorsal element and straps that wrap around the shoulders, waist and legs. Springs and counterweight levers partially bear the wearer's weight. The Bending Non-Demand Return (BNDR) [18,19] consists of a spring leveraged device that covers trunk and pelvis. Forces are exchanged at chest and upper leg levels. Happyback, Bendezy and BNR devices have been designed specifically for static stoop postures, common positions in crop harvesting [18,19].

The effects of passive exoskeletons are investigated in few studies [15,19–21], most of them include only a small number of participants and usually they are not shop floor workers, with the exception of [15]. All testing protocols involve a repeated measure type experimental design, including within-subject comparisons of with and without exoskeleton use [9,10].

In the paper, a passive exoskeleton to assist automotive workers in tasks that involve postures with elevated arms or require repeated arm motion is tested. The Levitate Technology passive exoskeleton [22] was chosen, since the device is engineered to support the wearer's arm when the arm is raised in static or quasi-static postures.

The research hypothesis was that the use of the Levitate exoskeleton is effective: (i) to increase the endurance time of static postures with elevated arms and (ii) to assist in repeated manual handling tasks of small loads. The test campaign also focused on possible issues associated to the user's acceptance, to the implementation of these devices in the automotive industry and to the risk assessment of the biomechanical workload in the design phase.

2. Materials and methods

2.1. Participants

31 healthy male operators volunteered for the research study. Workers were identified based on their

anthropometry (height in the range 170 – 180 cm), in order to fit the specifications of the exoskeleton prototype. In order to have a homogeneous sample, other inclusion factors were an age between 45 and 65 years and no limitation in strength or musculoskeletal disorders at the upper limbs. Participants were informed in full detail about aim and nature of the study and they signed an informed consent. The measurements were performed in accordance with the Declaration of Helsinki.

Two workers were discharged because their anthropometric measures were not fully compatible with the exoskeleton size. Participant mean height and mass were 174.9 cm ($SD \pm 2.3$ cm) and 81.6 kg ($SD \pm 9.1$ kg), respectively. Mean age was 51.5 y ($SD \pm 4.7$ y).

2.2. Exoskeleton description and fitting

The Levitate exoskeleton [22] is a lightweight wearable technology engineered to support the arms of workers who are exposed to repetitive arm motion and/or static elevation of the arms. The exoskeleton (Fig. 1a) consists of a metallic frame for the core and two armrests for the upper arms (elbow and forearm are not interested). Along the arm are present mechanical passive elements to partially relieve upper limb muscles and shoulder joints by transferring the weight of the arms from the shoulders, neck and upper back to the core body. The mechanical elements are ineffective when the arm is in a neutral position, while the support progressively increases when raising the arm. The gradual return of the arm to a neutral position is guaranteed by the weight of the arm itself. The angles of arm elevation at which the exoskeleton is active and the amount of support provided by the device can be customized (Fig. 1b). In fact, the exoskeleton comes with different sets of mechanical passive elements. The appropriate set is chosen in accordance to the wearer's arm weight and the task to be performed (i.e. the tool weight and the range of motion of the arm during the task).

The exoskeleton can be custom-fit regulating length of the core metallic frame, size of the armrests and shoulder and waist straps, so that the device can be worn like a backpack. A custom fitting is a key issue for comfort (moving seamlessly with the user and limiting intrusion into the workspace) and optimal performance. The size that was used as tester was a medium size, corresponding to P50 American male, classical percentile approach.

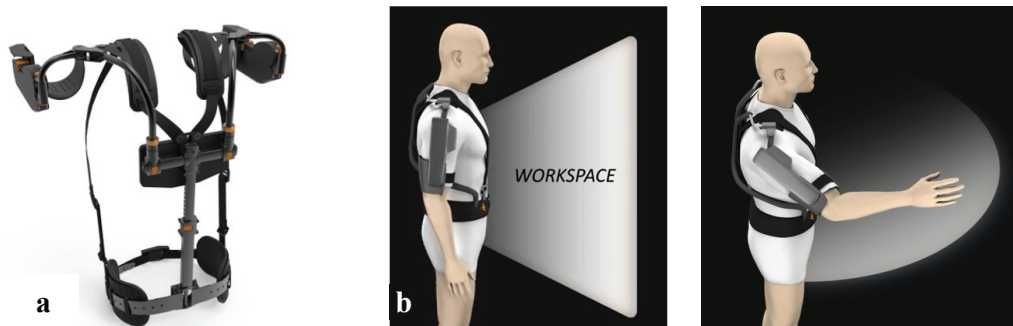


Fig. 1. Levitate technology: (a) structure of the exoskeleton, (b) workspace of the exoskeleton. (Images available at: <http://www.levitatetech.com>; accessed 02/03/2017).

2.3. Test protocol

All the tests were conducted at the ergonomics laboratory (Ergolab) of FCA (Fiat Chrysler Automobile) Manufacturing Engineering, tests were performed in the same day for each participant and they were video recorded using frontal and lateral camera. Three different tasks to be performed without and with the exoskeleton were designed: (1) static task, (2) repeated manual material handling task, (3) precision task. Semi-structured interviews were administered to the workers and rating scales were used to assess usability and user's acceptance of the device.

1. Static task

The worker was required to maintain a static posture: standing upright with extended arms (90° with respect the

trunk) while holding a load (Fig. 2a). The weight was represented by a car spoiler having a mass of 3.5 kg. The spoiler was placed on the forearm, so that the wrist was not involved.

Nor minimum nor maximum time was set, the worker stopped when he experienced fatigue or discomfort.

Data collected were: maintenance time of the static posture, video assessment of the maintenance of an upright trunk and extended arms, fatigue or discomfort sensation experienced by the worker.

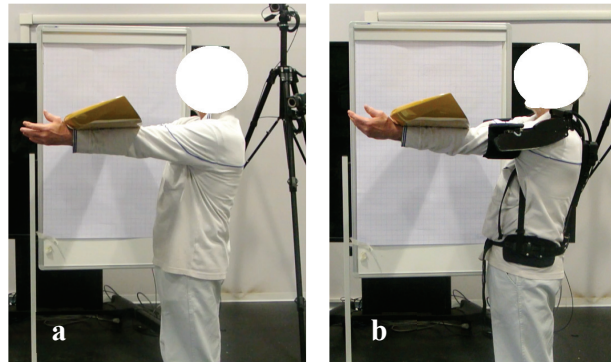


Fig. 2. Static posture task: (a) without exoskeleton; (b) with exoskeleton.

2. Repeated manual material handling task

The aim of the task was to evaluate the potential benefit (lessen muscle strain) introduced by the exoskeleton during a manual material handling activity vs. possible restriction to movements. The test involved a dynamic task with repeated movements with a wide range of motion of the shoulders joint. This task was developed from the FIT-HaNSA “Waist up” Protocol [23]. To simulate a real working task, the participant was requested to move an object with mass of 3.4 kg between two positions having different heights (Fig. 3a).

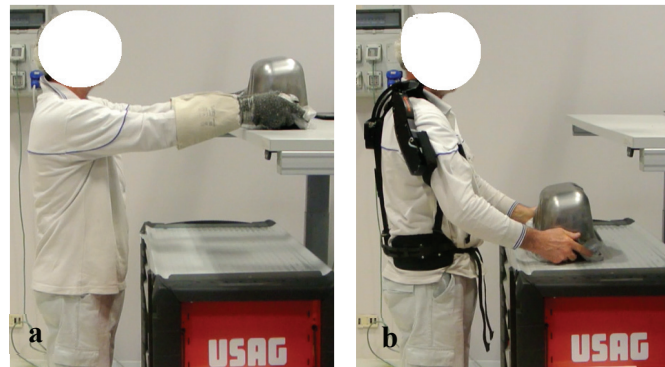


Fig. 3. Repeated manual material handling task: (a) without exoskeleton; (b) with exoskeleton.

The two positions were set at 0.9 m from the floor and at worker's shoulder height, respectively. The movements were paced at 30 actions/min using a metronome. The maximum duration of the task was set equal to 600 s. The participant could stop the test if experiencing fatigue, discomfort or was asked to stop after losing pace three times.

Data collected were: the number of performed lifting, assessment of the pace using the video recordings, and fatigue or discomfort sensation experienced by the worker.

3. Precision task

The main goal of the task was to evaluate potential benefit of the exoskeleton (lessen muscle strain, higher comfort rating and dexterity) during a precision task, with significant static load on the shoulder joint. The test consisted in tracing on a paper fixed on a billboard a continuous wavy line between two premarket traces (task

similar to a sealing operation). A felt-tip pen was used to trace the line, the billboard was custom placed at a height with respect to the participant's shoulder. The subject was standing, with the predominant arm almost extended (Fig.4) and he was not allowed to lower the arm except at the end of the task. As can be observed from the pictures of Fig. 4, five different wavy rows (with 27 arches for row) were present on the paper at different heights. The subject started at shoulder height and progressively moved upward to an overhead position. The participant was asked to maintain upright trunk and extended arm, but he was allowed to move parallel to the wall. The end of the task was at subject's will or at the end of the premarked guides.

Data collected were: the line traced by the operator, execution time, video assessment of the maintenance of an upright trunk and extended arms, and fatigue or discomfort sensation experienced by the worker.

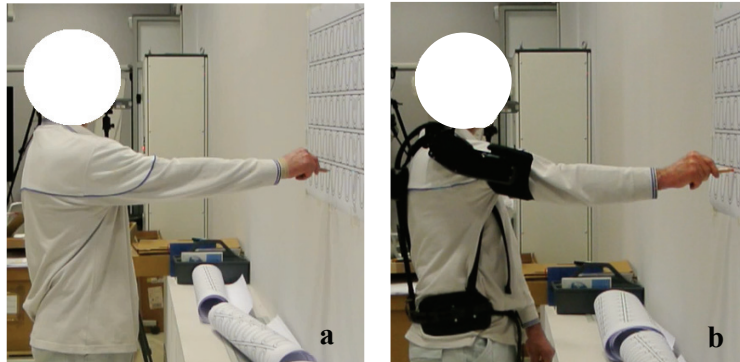


Fig. 4. Precision task: (a) without exoskeleton; (b) with exoskeleton.

4. Cognitive assessment

Several tools were used to acquire data and information in order to assess usability and acceptability of the exoskeleton. At the end of each task, both without and with the exoskeleton, a cognitive ergonomist held a semi-structured interview with the worker, aimed at understanding the quality of the interaction with the device. Through open questions, workers were encouraged to express their opinion and experience on aspects such as the efficacy of the support provided by the exoskeleton, the assistance in the task, the local perceived discomfort... In addition, during the interview, workers were asked to verbalize positive and negative features of the device by selecting among a list of “reaction adjectives”.

Other tools included Borg Scale, usability metrics questionnaire, TAM 2 questionnaire and a final focus group. The Borg scale [24], also known as RPE (Rate of Perceived Exertion), is a frequently used quantitative measure of perceived exertion and it was utilized to quantify the intensity level of the activities as perceived by the workers when tasks were performed without and with the exoskeleton. The usability metrics questionnaire helped in evaluating the efficacy, effectiveness and user's satisfaction of the device for the tasks. The questionnaire was based on a list of items relating to the main usability characteristics (freedom of movement, satisfaction, acceptability, reliability, interference, simplicity, usefulness, discomfort...) and it was customized from the literature and international standards. The Technology Acceptance Model 2 questionnaire (TAM2) [25] is commonly used to analyse the technology acceptance in relation to intention to use, perceived ease of use and perceived usefulness. The determinants include voluntariness, subjective norm, image, experience, job relevance, output quality and result demonstrability. The assessment by the usability metrics questionnaire and the TAM2 questionnaire was based on the workers' level of agreement with given statements pertaining the different items. For any given statement, workers had to choose a value on a Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree).

Following the experimental campaign, workers participated in a focus group. The moderator conducted the session and involved workers in discussing on the use of exoskeleton, focusing on positive and negative aspects in relation to their work context, and on the desirable characteristics of the device.

At worker arrival in the lab, the functioning of the exoskeleton was explained. He was also informed about the test protocol and that he could stop whenever he wanted, without completing the entire task or the whole protocol.

Personal data and anthropometric measurements were also collected to fill the database.

The worker was then asked to perform the static, repeated manual material handling and precision tasks without the exoskeleton (Figs 2a, 3a, 4a). Between the tests, adequate time was left to the worker to rest.

The exoskeleton was then regulated and the worker wore it. Using the anthropometric data and a table provided by Levitate Technology, two sets of mechanical passive elements were suggested. The worker tried both sets and then chose the most comfortable one. The participant was allowed to familiarize with the exoskeleton before asking him to repeat the tests with the exoskeleton (Figs 2b, 3b and 4b).

At the end of each task, both without and with the exoskeleton, a cognitive ergonomist interviewed the worker.

3. Results and discussion

According to the main aim of the test, quantitative and qualitative parameters were analysed.

1. Static task

In this test, the posture maintenance was controlled by visually inspecting the recorded video images and possibly, if this changed during the trial, the corresponding time was assumed as the end of the trial itself. Also a comparison of the postures without and with the exoskeleton was assessed, with particular attention to the arms and the spine. No substantial differences were detected.

In Table I mean values and SD of the task length with and without exoskeleton were reported. Also the time variation interval ($\Delta T = T_{\text{EXO}} - T_{\text{NO_EXO}}$) and the relative variation ($\Delta T\% = (T_{\text{EXO}} - T_{\text{NO_EXO}}) / T_{\text{NO_EXO}}$) were evaluated.

Table I: results of the static task

	$T_{\text{NO_EXO}}$ [s]	T_{EXO} [s]	Δt [s]	$\Delta t\%$
Mean	183.9	246.2	62.3	31.1%
SD	± 54.1	± 110.6		

The operators maintained the static posture for a mean time of 183.9 s and 246.2 s without and with the exoskeleton respectively, with a 31.1% relative longer time length in the second case. In particular, 25 operators increased the static holding with the exoskeleton, while 4 decreased it.

When interviewed, the workers declared that with the exoskeleton they perceived less fatigue, and more in general 26 operators found the exoskeleton action beneficial.

2. Repeated manual material handling task

In this trial, no operator went out of pace, they either continued for the entire test length (600 s) or asked to stop the trial. 12 operators endured for 600 s both without and with the exoskeleton, 11 decreased the time for which they endured when wearing the exoskeleton and finally 6 increased the endurance time when wearing the exoskeleton.

Table II: results of the repeated manual material handling task

	$T_{\text{NO_EXO}}$ [s]	T_{EXO} [s]	N° of actions NO EXO	N° of actions EXO
Mean	455.4	452.2	227.7	226.1
SD	± 152.9	± 178.0	± 76.5	± 89.0

In Table II mean endurance times and number of actions are reported. Results are comparable without and with the exoskeleton. First, it can be observed that this test has a ceiling effect and that the results are in some way contradictory. This can be explained considering the nature of the task itself and the feeling experienced by the workers. In fact, the test required a slightly adducted position of the shoulders. Most of the operators remarked that, when wearing the exoskeleton, part of the force they had to exert was aimed to maintain the adducted position against the device. Therefore, they experienced some discomfort, although they declared the device was helpful in raising the object.

3. Precision task

In this test, the posture maintenance was controlled by visually inspecting the recorded videos and also in this case no substantial differences were detected.

To analyse and quantify the performance obtained during this task, the wavy line was segmented into arches. The maximum number of arches was 135 distributed on 5 lines. Considering the test without exoskeleton, 6 operators filled all the 135 arches, while with the exoskeleton the number of operators increased to 19. In Table III the mean number of arches traced by each operator is reported without and with the exoskeleton. A significant increase of the number of traced arches can be observed when the workers worn the device. Also in this case for the number of traced arches there is a ceiling effect when the task was executed with the exoskeleton.

Table III: results of the precision task

	N° arches NO EXO	N° arches EXO	Time/arch NO EXO [s]	Time/arch EXO [s]	Δ N° arches	Δ% N° arches
Mean	85.8	114.6	4.3	4.2	28.8	33.6%
SD	±32.5	±31.1	±1.1	±1.1		

The mean time to trace each arch was calculated, independently from the achieved number of arches. Results without and with the exoskeleton were comparable.

The arches were then examined in order to assign a precision score. A full score of 10 was assigned to each arch, with an overall possible score of 1350. Four types of errors were identified based on how much the line traced by the worker was out with respect to the pre-marked traces. Weight factors were then assigned for type of error and row position. The Precision Index (PI) was calculated according to (1):

$$PI = \frac{1350 - \Sigma weight \cdot error}{1350} \% \quad (1)$$

Overall (Table IV) the PI increased when wearing the exoskeleton, 90% of the workers performed better when wearing the device, since the PI sensibly increases.

Table IV: Precision Index

	PI % NO EXO	PI % EXO	Δ PI %
Mean	27.0	43.7	16.7
SD	±17.2	±17.4	

In general, the operators were unanimous to assess that in this task the presence of the exoskeleton was beneficial both for the perceived fatigue and for the precision of the execution. No drawbacks associated to the use of the device were pointed out.

Cognitive assessment

During the interviews, workers judged positively the exoskeleton and declared it helped them to carry out the tasks with less physical and mental effort. The device was perceived particularly useful in the precision task. In the list of “reaction adjectives”, workers chose positive adjectives to describe qualities like easy to use, innovative, easy to understand, effective, efficient, and useful. Workers’ responses to the usability metrics questionnaire highlighted a good human-device interaction, but, on the other hand, revealed that the operators considered the work-device interaction critical.

TAM2 results showed stronger agreements for statements that imply perceived ease of use, voluntariness and result demonstrability. Respondents were more neutral on aspects like job relevance, intention to use, image, and output quality. Focus group results were similar: workers affirmed that the exoskeleton can be useful in carrying out work activities, but the use should be non-mandatory.

4. Conclusions

Passive exoskeletons are taken into account for possible use as supporting devices in the industrial manufacturing environment. FCA, after a throughout literature research and benchmarking of available commercial devices, has

planned a testing campaign to define applicability, usability and implementation of exoskeletons in working tasks.

In this paper, the experimental activity on the passive exoskeleton of Levitate Technology is presented. Twenty-nine workers from a FCA automotive plant participated in the tests. Qualitative and quantitative results showed a positive effect of the exoskeleton for those activities that involve a posture with raised arms. Workers increased their performance (average improvement 30%) when wearing the exoskeleton and perceived less fatigue. Encouraging data also emerged from the workers' interview. Still, during the focus group, workers affirmed that the use of the exoskeleton should be on a voluntary-base.

Before adoption in the real work environments, more information on worker's acceptance of the device and long-term use is needed. Industry experience can reveal obstacles to worker's acceptance that are not evident in a controlled laboratory environment. In addition, the introduction of such devices requires a deeper understanding of the biomechanical workload in exoskeleton-assisted work tasks and of the potential repercussions in the work methods already in design or industrialization phase, with a growing need for holistic methods for risk assessment such as the EAWS method. The risk factors influenced by the use of passive exoskeletons are the posture, in the specific case the posture of the shoulder, the request of force and the static muscle effort, which are covered by the structure of EAWS.

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